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With the funding provided under this grant, we have procured equipments for creating a sample of ^{87}Rb atoms with ultracold temperature (35 nano-Kelvin) and high density (10^{12}cm^{-3}), using Raman cooling via velocity selective coherent population trapping. We have already been able to create a magneto-optic trap (MOT) of ^{87}Rb atoms, loaded from background rubidium vapor inside the trap chamber. We have achieved a density close to 10^{10}cm^{-3}, at a temperature of 80 μK, which is typical of such a trap. The next step is to load the trap from a chirp-slowed atomic beam, and use a repumping beam which is dark at the center. This is expected to increase the density to about 10^{12}cm^{-3}. We will then Raman- cool the sample to about 35 nano-Kelvin, thus yielding a sample for a rubidium fountain clock. The fountain clock loaded from this source is expected to have a short term accuracy that is more than two orders of magnitude better than existing cesium fountain, which are already a factor of two better than existing cesium beam clocks used as primary frequency standards.

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FINAL REPORT

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NANO-KELVIN COOLING OF DENSE ATOMS FOR AN ULTRA-STABLE FOUNTAIN ATOMIC CLOCK

By

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ABSTRACT

With the funding provided under this grant, we have procured equipments for creating a sample of ^{87}Rb atoms with ultracold temperature (35 nano-Kelvin) and high density (10^{12}cm^{-3}), using Raman cooling via velocity selective coherent population trapping. We have already been able to create a magneto-optic trap (MOT) of ^{87}Rb atoms, loaded from background rubidium vapor inside the trap chamber. We have achieved a density close to 10^{10}cm^{-3}, at a temperature of 80 μK, which is typical of such a trap. The next step is to load the trap from a chirp-slowed atomic beam, and use a repumping beam which is dark at the center. This is expected to increase the density to about 10^{12}cm^{-3}. We will then Raman- cool the sample to about 35 nano-Kelvin, thus yielding a sample for a rubidium fountain clock. The fountain clock loaded from this source is expected to have a short term accuracy that is more than two orders of magnitude better than existing cesium fountain, which are already a factor of two better than existing cesium beam clocks used as primary frequency standards.

1.0 INTRODUCTION.

The funding provided under this grant was to be used to procure equipments for creating a sample of ^{87}Rb atoms with ultracold temperature (35 nano-Kelvin) and high density (10^{12}cm^{-3}), using Raman cooling via velocity selective coherent population trapping. Such a sample of atoms can be used as a source for a rubidium fountain clock, which is expected to have a short term accuracy that is more than two orders of magnitude better than existing cesium fountain, which are already a factor of two better than existing cesium beam clocks used as primary frequency standards.

The original list of equipments included a Ti:Sapphire ring laser, along with a 20 W Ar+ pump laser, four high frequency electro-optic modulators, and two high frequency photo detectors. During the tenure of the grant, we were able to obtain some of these equipments from an alternative source. Specifically, Dr. Philip Hemmer of the Rome Laboratory was kind enough to lend us the high frequency modulators and detectors. This created an opportunity to use the money allocated for these parts in ways that would expedite our experiment. First, it was now possible to procure some other equipments that are necessary for our project. Second, there was now an option to purchase an upgraded model (899-05) of the Ti-Sapphire laser, with frequency stability and tunability directly suitable for the demanding conditions of an atom trap. If we were to buy the model listed originally in the grant (899-05), we would have to upgrade it ourselves, using additional parts, labor, and time. As required under the terms of this grant, we notified the AFOSR grant monitor of this change in our equipment requirements, in advance of any procurement.

2.0 PROCUREMENT OF EQUIPMENTS

Table 1 summarizes the equipments we procured under this grant. The 20W Argon ion laser (Innova 400) is used as a pump for the Ti-Sapphire laser. The Ti-Sapphire laser (899-05) produces a tunable source of single frequency radiation, with an output power of more than 2W over the wavelength range of 780-795 nm. The free-running linewidth of this laser is about 10 MHz (which is to be contrasted with the 2 GHz linewidth of the model 899-01). The high-frequency amplifier is used to drive the 6.8 GHz electroptic modulators. The pneumatic valve is used to protect the trap vacuum against power failures. The pulse generator is used to turn the trapping beams off and turn a probe beam on in order to measure the density of the trapped atoms. The shutter control system provides a digital interface for sequencing ferro-electric liquid crystal shutters. The data acquisition system runs the Labview system for real time data acquisition, analysis, and feedback.

Table 1: List of Equipments Procured

Item #	*Date*	*Name of Item*	*Manufacturer*	*Part #*	*Cost($)*
1.	12/08/95	Argon Laser	Coherent Inc.	Innova 400	56,059.88
2.	12/08/95	Ti-Sapphire Laser	Coherent Inc.	899-05	56,560.00
3.	05/14/96	High-frequency Amplifier	MITEQ, Inc.	AMF-58-040080-70-29.5P-S	2,713.75
4.	05/24/96	Pneumatic Valve	MDC Vacuum Products Co.	GV-1500V-P	1,460.63
5.	08/01/96	Digital Delay Pulse Generator	Stanford Research System	DG 535	3,519.95
6.	08/23/96	Shutter Control System	Computer Decisions	XPRNT76-5/90-810/ACT	1,399.00
7.	08/23/96	Data Acquistion System	Mainboard Computer Co.	MB-P120	1,619.00

2.0 STATUS OF EXPERIMENTS

As the first step toward developing a rubidium fountain atomic clock loaded from a dense sample of Raman-cooled atoms, we have constructed a magneto-optic trap. In this trap, atoms remain confined in the center of a quadrupolar magnetic field, in the presence of three pairs of orthogonal laser beams. The trap is loaded from the background rubidium vapor. This vapor is introduced into the chamber by opening momentarily a valve connecting to a smaller chamber containing a pellet of rubidium. The trapping beams are tuned to a cycling transition in the D_2 manifold of rubidium. The repumping is provided by a sideband generated via electrooptic modulation.

We have succeed in trapping both isotopes of rubidium (^{85}Rb and ^{87}Rb) in our chamber. For the fountain clock, however, we are concentrating on ^{87}Rb, which has a much higher hyperfine frequency separation. The trapped sample of ^{87}Rb atoms have a density close to 10^{10} atoms per cm^3, at a temperature of about 80 μK. These numbers are typical for a trap loaded from background vapor.

To determine the density in the trap, we use a sequence of pulses. The trapping beams are on for about 2 sec, followed by a period of about 5 msec during which the trapping beams are turned off, and a very weak probe beam is turned on. The repumping beam is kept on all the time, in order to prevent escape to untrappable ground states. The absorption of the probe beam, detected by a box car integrator, yields directly the density of the trap. The temperature, on the other hand, is determined by ballistic expansion methods. Briefly, the trapping and repumping beams are turned off, so that the atoms fall freely under gravitational acceleration. During the fall, the trap diameter grows, at a rate determined by the mean velocity (which in turn determines the temperature). The trap size is measured by imaging fluorescence with a video camera from a probe beam at two different instances. The degree of ballistic expansion during the known time interval is used to infer the temperature.

In order to maximize the use of the equipments procured under this grant, we have used the Ti-Sapphire laser to perform other experiments, during periods when the vacuum system for the trap is serviced. In particular, we have demonstrated ultrafast, high efficiency, low power optical phase conjugation using four wave mixing via Raman coherent population trapping among the Zeeman sublevels of any given hyperfine transition, in a rubidium vapor cell. This experiment has three strong implications. First, it makes feasible the construction of a practical, portable optical phase conjugation using a single semi-conductor laser, to be used in projects such as high speed aberration correction in turbulence imaging. Second, it generalizes and simplifies the extremely efficient scheme of Raman phase conjugation to virtually any atomic or molecular system, thus covering almost all wavelengths of potential interest. Finally, it offers the possibility of generating continuous wave, spatially broadband squeezing of quantum noise, which in turn would enable detection of very faint images, thus enhancing the data transport capacity of parallel optical interconnects.

3. FUTURE WORKS

We are continuing our efforts to realize a rubidium fountain atomic clock loaded from a dense sample of Raman-cooled atoms. The next step in this direction is to increase the trap density. To achieve this, the trap will be loaded from slow atoms generated by a chirp-slowed atomic beam. In addition, the repumping beam is to be modified so that it has a dark spot at the center. These two modifications, currently underway, is expected to yield a density approaching $10^{12}cm^{-3}$. The next step would be to apply a set of beams that will cool the sample down to 35 nK, using three dimensional, cooling assisted, velocity selective coherent population trapping. During this cooling process, the atoms will be kept confined inside a blue far off-resonant trap (FORT), created by focusing a donut mode from an Argon laser to a 10 μ spot. The cooled sample of dense atoms will then be launched vertically, creating a "fountain" of atoms. The launched atoms will cross a

microwave cavity at 6.8 GHz twice, yielding Ramsey fringes to be used in stabilizing the microwave source driving the cavity, thus realizing a rubidium fountain clock.

As discussed above, the utilization of the equipments is optimized if other experiments are performed during routine maintenance of the vacuum components of the trap. To this end, we will continue to pursue the use of our recently discovered method of optical phase conjugation for applications. These include generation of spatially broadband squeezing of quantum noise, as well as high speed correction of aberration in turbulence imaging.